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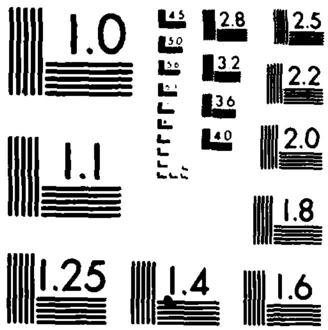

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SWIRL INDUCED BY LARGE AREA FIRES

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Swirl has been suggested as the mechanism responsible for high fire-wind velocities and exceptional plume rises from large area fires. The potential sources of vorticity that could result in a swirling central column are examined. Coriolis forces produce only a small tangential velocity component for the time and length scales appropriate to a city size fire. Similarly, asymmetries in fuel load or burning distribution cannot generate sufficient swirl velocities to influence the plume motion or fire-wind velocities. Neither eddies or rotational systems of scale much larger or smaller than the fire radius can produce swirl. Wind systems with wavelength similar in scale to the fire diameter produce only a negligible tangential velocity component. As a consequence, plumes produced by large area fires are not likely to swirl.

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PREFACE

This report was prepared by Pacific-Sierra Research Corporation (PSR), a subsidiary of Eaton Corporation, for the Defense Nuclear Agency (DNA). The work was done under contract DNA 001-85-C-0089, and supervised by Dr. Michael J. Frankel.

In previous PSR studies, the generation of fire winds by large area fires has been considered. In this report, the possible mechanisms for generating central column swirl are examined, and induced tangential velocities are calculated for a 10-km radius large area fire.

CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement

MULTIPLY ⟶ / TO GET ⟵	BY ⟶ / BY ⟵	TO GET / DIVIDE
angstrom	1.000 000 X E -10	meters (m)
atmosphere (normal)	1.013 25 X E +2	kilo pascal (kPa)
bar	1.000 000 X E +2	kilo pascal (kPa)
barn	1.000 000 X E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 X E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical)/cm^2	4.184 000 X E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 X E +1	*giga becquerel (GBq)
degree (angle)	1.745 329 X E -2	radian (rad)
degree Fahrenheit	$t_K = (t°f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 X E -19	joule (J)
erg	1.000 000 X E -7	joule (J)
erg/second	1.000 000 X E -7	watt (W)
foot	3.048 000 X E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 X E -3	meter^3 (m^3)
inch	2.540 000 X E -2	meter (m)
jerk	1.000 000 X E +9	joule (J)
joule/kilogram (J/kg) (radiation dose absorbed)	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 X E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 X E +3	kilo pascal (kPa)
ktap	1.000 000 X E +2	newton-second/m^2 (N-s/m^2)
micron	1.000 000 X E -6	meter (m)
mil	2.540 000 X E -5	meter (m)
mile (international)	1.609 344 X E +3	meter (m)
ounce	2.834 952 X E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 X E -1	newton-meter (N·m)
pound-force/inch	1.751 268 X E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 X E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 X E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 X E -2	kilogram-meter^2 (kg·m^2)
pound-mass/foot^3	1.601 846 X E +1	kilogram/meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 X E -2	**Gray (Gy)
roentgen	2.579 760 X E -4	coulomb/kilogram (C/kg)
shake	1.000 000 X E -8	second (s)
slug	1.459 390 X E +1	kilogram (kg)
torr (mm Hg, 0° C)	1.333 22 X E -1	kilo pascal (kPa)

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1

INTRODUCTION

Large area fires, sometimes called firestorms, differ in many ways from small conçentrated flames, forest fires or even isolated urban fires. The distribution of buoyancy over a large area can produce high winds that flow inward from all directions once the firestorm has been established. The fire winds are the source of oxygen for the fire, and also tend to limit its spread by forcing the flames inward. Since the burning zone does not move, another phenomenon typical of firestorms--complete burning of all combustibles--can result. From dimensional arguments, the average inflow velocity at the fire parameter can be shown to grow with the cube root of the equivalent fire radius. Thus, only fires of area above some minimum will necessarily be stationary and develop into firestorms. That area (or typical radius) is obtained when the inflow velocity is higher than the greatest wind a fire can spread against. That value, although not well established, is evidently a function of the density of available combustibles, the distribution of ignitions, and the shape of the overall fire front. One value quoted in the literature [Glasstone and Dolan, 1977] is 8 mph or 3.5 m/s, but that value is probably low, as indicated by the February 1945 Dresden fire [Irving, 1963]. A fire diameter of $O(10^3)$ m is probably sufficient to be stable in such ambient winds. Area fires of that size are unusual which may explain the rarity of firestorms. Nevertheless, natural disasters such as volcanic eruptions or earthquakes could conceivably ignite large areas simultaneously so that large inflow velocities are obtained.

Large area fires have been produced artificially by patterned simultaneous ignitions in firebombing during World War II, by planned ignitions for forest clearing [Small, 1985], and by nuclear explosions.

It has been suggested [Emmons, 1965; Long, 1967] that the high winds and exceptionally tall plumes related to firestorms require the existence of swirling motions. Sketchy (mostly anecdotal eyewitness) evidence from the 1943 Hamburg, Germany fire has been since quoted [Carrier et al., 1985] to support that notion. If true, the existence of swirl has critical bearing on the plume generated by a large area fire and as a consequence, on the injection and spread of combustion products through the atmosphere and on the possibility of a nuclear winter. Massive swirling hinders entrainment and mixing, narrows the plume (by centripetal acceleration of the lighter plume elements), and drives it higher--possibly into the stratosphere where particles are likely to have much longer residence times.

SECTION 2
POSSIBLE CAUSES OF SWIRL

In this section, we discuss the possible physical mechanisms that can cause a large area fire plume to swirl. The fires considered have burning areas greater than 1 km^2.

Basically, the buoyancy generated by an area fire induces a radial inflow of ambient air at ground level and an upward convection of combustion products [Larson and Small, 1982; Small, Remetch, and Brode, 1984; Small and Larson, 1986]. Thus, swirl is not an intrinsic characteristic [Morton, 1970] of the flow field and must be caused by some outside agent, for example, the earth's rotation. The area affected by the fire can have a radius of $O(10^4)$ m so that Coriolis-type effects are not obviously negligible.

The Coriolis force (acceleration) can be written as

$$\vec{a}_c = 2\vec{\omega} \times \vec{u} \quad , \tag{1}$$

where ω is the earth's angular velocity (actually its component perpendicular to the surface, $\omega = 7.27.10^{-5} \sin\phi$ rad/s). The inflow velocity u, is a function of the distance from the fire center. The tangential velocity at the fire rim R_o at time T due to the Coriolis effect is

$$v = \int_0^T 2\omega u \, dt = - \int_s^{R_o} 2\omega u \, dr/u = 2\omega(s - R_o) \quad , \tag{2}$$

where s is the initial distance of the particle that reaches the rim at time T. A mature flow field is assumed at T = 0. In reality, the flow develops over some period of time. The minus sign indicates inward velocity u. That velocity will increase with time, a phenomenon

usually called "spin up." However, the fire only burns for a limited time, which can be written as

$$t_{max} = \frac{mc}{J} \quad , \tag{3}$$

where m is the combustible loading mass per unit area, C the caloric equivalent of the combustibles per unit mass, and J the rate of conversion of chemical energy (burning) per unit area. The latter is sometimes presented per unit volume, in which case the flame height H_f needs to be considered (i.e., $(J)_{area} = (J)_{volume} \cdot H_f$). The elapsed time t, can be written

$$t = -\int_s^{R_o} \frac{dr}{u} = -\int_s^{R_o} \frac{rdr}{U_o R_o} = \frac{R_o}{2U_o}\left[\left(\frac{s}{R_o}\right)^2 - 1\right] \quad , \tag{4}$$

where the inflow velocity u was assumed similar to that generated by a sink flow [i.e., inversely dependent on distance ($u \sim 1/r$)]. This implies that the inflow into a large fire system is mostly contained in a shallow surface layer. Such flows have been calculated [Small, Remetch, and Brode, 1984; Penner, 1985]. From Eqs. (2) and (4), and recalling that $t \leq t_{max}$,

$$\frac{v}{U_o} \leq 2\,\frac{\omega R_o}{U_o}\left(\sqrt{1 + \frac{2t_{max}U_o}{R_o}} - 1\right) \quad . \tag{5}$$

Using typical combustible loadings (see Table 1) and calculations of large area fire flow fields as input conditions, we obtain $(v/U_o)_{max}$ of approximately 0.4 to 0.5 (for a circular area fire, toward the end of the burn). That is, the total velocity is never more than 13 percent above the radial influx alone. Data for the Hamburg

fire, which has been quoted as possibly swirling, has been included as case III in Table 1. It is clear that some swirl can be generated by the earth's rotation, but it is much too small to contribute significantly to the velocity field. A typical hurricane calculation (case IV) shows that long spin up times are required to cause very large increases in the wind speeds. The results of those simple calculations are consistent with observations. Thus, it seems reasonable that the present model properly estimates the potential for swirl from Coriolis accelerations.

A different possible source of swirling motions lies in nonuniformities in the burning area, or its surroundings. Those inhomogeneities can be in the type and concentration of combustibles, in the topography of the area, or in the time interval of the ignitions. Each of those effects can cause nonradial (tangential) components in the flow field. Conservation of angular momentum will cause the tangential motions to be intensified as the flow elements involved move radially closer to the fire epicenter.

To describe that effect in a more quantitative manner, consider an example of a square city block of side length a, which is burning uniformly, but the access routes for incoming air (the surrounding streets) are blocked (e.g., by rubble). All the air feeding the fire comes in from two channels (streets) of width b, such that the vorticity is increased rather than reduced. That is a worst-case scenario, as any air coming in from other streets will reduce the asymmetry.

The circulation induced by the nonradially centered inflow is

$$\Gamma = 2u_1 a \quad , \tag{6}$$

where u_1 is an appropriately averaged speed in the street. This can be written as

Table 1. Calculation of swirling component of velocity at ground level in vicinity of large area fire.

Case[a]	R_o(m)[b]	$J(J/m^2 \cdot s)$[c]	U_o(m/s)[d]	T_{max}(h)[e]	V(m/s)[f]	V/U_o[g]	$V_t = V^2 + U_o^2$[h]
I	10000	10	12.9	2.07	6.56	0.504	14.6
II	5000	10	9.5	2.07	3.93	0.414	10.3
III	1000 to 2200	7	--	5	3.5	0.49	7.8
IV	10^5	--	30	48	74.37	2.48	80.2

a
Case I = numerical model of 10-km radius fire [Small, Remetch, and Brode (1984)]; case II = same as case I, fire radius is 5 km; case III = Hamburg firestorm, data from Carrier et al. [1985]; case IV = hurricane of 100-km radius, at latitude 30°N, inflow velocity taken from extrapolation of large fire sink calculation ($R^{1/3}$ dependence); buildup time for hurricane taken as 48 h.

b
Fire radius.

c
Heat addition rate per unit fire area.

d
Radial inflow speed at R_o.

e
Time to total burnout (actual full strength fire duration for case III).

f
Tangential speed due to Coriolis effect, at fire perimeter.

g
Total velocity at fire perimeter.

$$u_1 = \frac{\dot{M}}{\rho A} = \frac{\dot{M}}{\rho hb} , \tag{7}$$

where M is the mass of air drawn in per unit time, ρ is its density, and h the inflow region height. The air flux can be related to the fire by

$$\dot{M} = \frac{BSL}{t} , \tag{8}$$

where B is the fuel loading, S the stoichiometric ratio, L the air excess ratio, and t the burning time, weighted so that a uniform burning rate is assumed. From Eqs. (6) through (8)

$$\Gamma \propto \frac{LSBa}{\rho htb} = \frac{\dot{M}a}{\rho hb} , \tag{9}$$

i.e., the circulation produced is proportional to the burning rate and burning unit size and inversely proportional to the available air entry channel size.

Each of those variations can happen on different scales. For example, individual buildings on a block may burn at different rates, or produce different levels of heat release per unit time. This is an O(10)-m scale. Streets will usually not burn, so that blocks are separated. Next, there could be a gradation of buildings from residential to commercial and industrial zones, i.e. a scale of hundreds of meters to kilometers. Any variations that have length scales much smaller than the equivalent radius of the fire are probably not significant, as their effects on rotation will cancel out on the scale of the entire fire. Thus, if a typical block-edge causes swirling in the clockwise direction, there is a high probability that opposite rotation of similar strength will occur in another street. The total over many blocks should roughly cancel out with the residual circulation

being inversely proportional to the number of units of combustion N (burning blocks). That can be written as

$$\Gamma_{total} \propto \frac{1}{N} \sum \Gamma_i \quad . \tag{10}$$

The sum tends to zero as N becomes large.

Alternatively, variations on scales much larger (hundreds of kilometers) than the fire scale are probably negligible too as the tangential components of flow they produce are very small.

Thus, we are left with nonuniformities of the scale of the fire. Those might be topographical (a hill or mountain, or a lake) or a change in neighborhood character as described previously. Before discussing them quantitatively, further details of the relation between those nonuniformities and swirling motions are needed.

A nonradial inflow (streamline) pattern can be expected if the burning area is not axisymmetric, since the local (near-field) inflow is normal to the fire front. Thus, there will be spreading of streamlines near concave parts of the perimeter, and concentrations next to convex sections. Perimeter shape effects alone, however, will not produce large scale net vorticity, as the tangential components cancel out for a uniform strength fire in a closed, simply connected region (i.e., $\Gamma = \oint \vec{V} \cdot d\vec{s} = 0$). The cancellation may not be perfect, however, if the burning is nonuniform. For example, an elliptical or lunar shaped area with greater burning intensity at one end can produce a net tangential component at any given circle surrounding the fire zone. Also, if a nonuniform burning area is located (for example) on the side of a hilly ridge, the horizontal inflow asymmetry is enhanced, leading to possible net vorticity.

Detailed predictions of the possible swirling motions, produced by nonuniformities in the fire and fuel bed, depend on a great variety of possibilities. Some estimates of the upper limits of rotation resulting from this class of vorticity generators are presented.

We now estimate the vorticity produced by a 10-km radius fire. The example city is bordered on one side by a steep mountain range. The fire burns an asymmetrically loaded area, with average combustible density on the right half of the fire zone twice that of the left. Similarly, the burning rate is twice as large in the right half. The heat release Q_A in the left fire zone is assumed 1 kW/m^3; roughly that from an area fire in an average density city. A uniform heat release of that magnitude can generate inflow speeds of about 13 m/s in the "mature" stage of the fire [Small, Remetch, and Brode, 1984]. We now assume that the mountains reduce the inflow from the sector they surround by a factor of 2 (over one-half of the circumference). Each of these inhomogeneities (topography and fire intensity) separately would not cause swirling, but the combination conceivably could. The offset distance Δ of the weighted center (from the geometrical center) of the fire is related to the heat release by

$$\Delta = \frac{4}{3}\,\frac{R}{\pi}\left(\frac{Q_B - Q_A}{Q_A + Q_B}\right) . \tag{11}$$

In this example, $Q_B = 2$ kW/m^3, $Q_A = 1$ kW/m^3, and $\Delta = 0.141\ R = 1.4$ km. Assuming a linear relationship between heat release rate and induced velocity, then $V_B = 2\ V_A$. This is not strictly true [Small and Larson, 1986], but is a sufficient approximation for this calculation.

The circulation induced by the asymmetries in burning and topography is

$$\Gamma = \oint \vec{V} \cdot d\vec{s} = \frac{2}{3}\, cR(Q_B - Q_A)\left(\frac{4}{3\pi} - 1 + \sqrt{1 + \Delta^2}\right) . \tag{12}$$

The constant c relates the heat release to the induced fire winds.

$$c = \frac{V_{A1} + V_{A2}}{2Q_A} = \frac{V_{B1} + V_{B2}}{2Q_B} = 13 \quad \frac{\mathrm{m/s}}{\mathrm{kW/M^3}} . \tag{13}$$

The circulation is then $\Gamma = 3.8 \times 10^4\ m^2/s$, and the induced tangential velocity (at an altitude above the hills) about 0.60 m/s. This assumes no necking of the plume. If the plume cross-section area is reduced by 3/4 (half the fire radius), then the induced tangential velocity is only 1.2 m/s. For either a uniform heat release or uniform topography, no swirl component is introduced. For the combination of asymmetries and even with an extreme necking of the plume (worst-case analysis), the swirl generated is essentially negligible.

Perhaps the mechanism most likely to induce swirling [Carrier et al., 1985] is vorticity already existing in the atmosphere--brought in, and concentrated by the ground level inflow of the fire. We can reasonably exclude as a source extreme weather systems such as storms or hurricanes (1) because of their relative rarity, and (2) because they will probably help subdue the fires, and in any case, cause much larger changes in any plume before merging with it to produce a swirling plume. The effect of small eddies [$R = 0(100)$ m or less] can also be neglected; they occur frequently, but their effect cancels statistically or quickly decays with time (at a rate inversely proportional to the eddy size and viscosity).

The greatest influence may result from horizontal wind gradients or eddies of wavelength comparable to the fire diameter. Such gradients and eddies can be produced by winds passing suitable topography upstream of the fire [Hunt et al., 1978]. The effect is equivalent to having a tangential (swirl) velocity of one-half the field velocity difference.

A reasonable upper limit for velocity differences from such gradients is about 10 m/s, which means that a tangential component of 5 m/s is expected. Such values would be characteristic of windy conditions. Higher values could result under storm conditions. Nevertheless, such shears are not large enough to cause rapid swirling. The vorticity generated is of similar order as those previously discussed.

In view of the above, it seems justified to reexamine popular conceptions about the Hamburg fire. The positioning of the eyewitnesses--especially those in streets relatively close to the fire

perimeter, in part explains the reported impressions of "very high winds and swirling." The inflow winds are in general channeled down streets and probably more so in old, tightly packed cities like Hamburg. That causes an increase in speed due to two reasons: (1) the decrease in available area, which may be a factor of 2 to 3; and (2) the Borda effect [Milne-Thomson, 1968] which causes flow in constricted areas to neck down further and utilize only about one-half of the available area. Thus, for city streets or natural channels, increases by a factor of 4 to 6 can be expected over the global or average inflow velocities (see Table 1). Accordingly, instead of 7 m/s (case III of Table 1) it may not be surprising to observe peak radial speeds of 35 m/s (~ 80 mph).

Also, the streets were not necessarily perpendicular to the flame perimeter so that flow down those urban canyons could be interpreted as having a tangential (swirling) component. Local fire whirls could be shed at various locations along the perimeter. However, the total vorticity for the whole fire system is still negligible. Thus the impressions of ground-level observers do not necessarily infer large-scale organized plume swirling motions.

Finally, swirl is not a prerequisite to the generation of large velocity fire winds. Larson and Small [1982a,b] and Small and Larson [1986] have demonstrated analytically, and Smith, Morton, and Leslie [1975], Small, Remetch, and Brode [1984], and Penner [1985], have shown in hydrocode simulations that pressure gradients generated by the fire-produced buoyancy distribution account for the high-velocity fire winds.

SECTION 3
CONCLUSIONS

The analysis presented in the previous section shows that all the factors considered do not cause appreciable swirling by themselves, even though the most extreme conditions were examined. Thus, for the question, Can the plume resulting from a large area fire swirl? the answer is, probably not. For rather unusual combinations of conditions, such as nonuniform fires burning for a long period (very high combustible loading not easily accessible to air), in an area partially bounded by hills, swirl velocities large enough to be noticeable (although not large enough to significantly affect the plume rise in the atmosphere) may occur--especially at the later stages of the fire. That explains why most observed large fire plumes [including experimental fires such as Meteotron (Church, Snow, and Dessens, 1980), Flambeau (Countryman, 1969), and Chapleau (Small, 1985)] did not swirl.

SECTION 4

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ATTN: DB-6E2 C WIEHLE
ATTN: RTS-2B
ATTN: WDB-4CR

DEFENSE NUCLEAR AGENCY
ATTN: RAAE
2 CYS ATTN: SPTD
ATTN: STSP
4 CYS ATTN: STTI-CA

DEFENSE TECHNICAL INFORMATION CENTER
12 CYS ATTN: DD

FIELD COMMAND DEFENSE NUCLEAR AGENCY
ATTN: FCTT W SUMMA
ATTN: FCTXE

JOINT STRAT TGT PLANNING STAFF
ATTN: JLKS

DEPARTMENT OF ENERGY

UNIVERSITY OF CALIFORNIA
LAWRENCE LIVERMORE NATIONAL LAB
ATTN: J BACHOVSKY
ATTN: N ALVAREZ
ATTN: R PERRETT

LOS ALAMOS NATIONAL LABORATORY
ATTN: DR D CAGLIOSTRO

OTHER GOVERNMENT

DEPARTMENT OF COMMERCE
ATTN: H BAUM
ATTN: R LEVINE

DIRECTOR, FFASR
ATTN: C CHANDLER

FEDERAL EMERGENCY MGMT AGENCY
ATTN: H TOVEY
ATTN: OFC OF RSCH/NP H TOVEY

OFFICE OF EMERGENCY SERVICES
ATTN: W TONGUET

DEPARTMENT OF DEFENSE CONTRACTORS

CALIFORNIA RESEARCH & TECHNOLOGY, INC
ATTN: M ROSENBLATT

CARPENTER RESEARCH CORP
ATTN: H J CARPENTER

CHARLES SCAWTHORN
ATTN: C SCAWTHORN

FACTORY MUTUAL RESEARCH CORP
ATTN: R FRIEDMAN

IIT RESEARCH INSTITUTE
ATTN: H NAPADENSKY

INSTITUTE FOR DEFENSE ANALYSES
ATTN: L SCHMIDT

KAMAN SCIENCES CORP
ATTN: E CONRAD

KAMAN TEMPO
ATTN: DASIAC

KAMAN TEMPO
ATTN: DASIAC

MCDONNELL DOUGLAS CORP
ATTN: J KIRBY
ATTN: J PECK

MISSION RESEARCH CORP
ATTN: J BALL

MODELING SYSTEM, INC
ATTN: G BERLIN

NOTRE DAME DU LAC, UNIV OF
ATTN: T J MASON

PACIFIC-SIERRA RESEARCH CORP
2 CYS ATTN: D WEIHS
ATTN: H BRODE, CHAIRMAN SAGE
2 CYS ATTN: R SMALL

R & D ASSOCIATES
ATTN: D HOLLIDAY
ATTN: F GILMORE
ATTN: R TURCO

RAND CORP
ATTN: P DAVIS

RAND CORP
ATTN: B BENNETT

DEPT OF DEFENSE CONTRACTORS (CONTINUED)

SCIENCE APPLICATIONS INTL CORP
ATTN: M DRAKE
ATTN: M MCKAY

SCIENCE APPLICATIONS INTL CORP
ATTN: J COCKAYNE

SCIENTIFIC SERVICES, INC
ATTN: C WILTON

STAN MARTIN ASSOCIATES
ATTN: S MARTIN

SWETL, INC
ATTN: T PALMER

TRW ELECTRONICS & DEFENSE SECTOR
ATTN: F FENDELL

END

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